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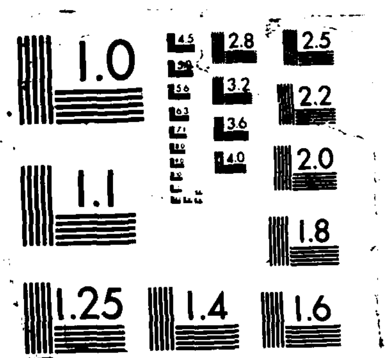
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HUMAN RESOURCES

MEASUREMENT AND EFFECTS OF TRANSPORT DELAYS IN A STATE-OF-THE-ART F-16C FLIGHT SIMULATOR

Scott J. Horowitz, Capt, USAF

OPERATIONS TRAINING DIVISION
Williams Air Force Base, Arizona 85240-6457

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In recent years, the military community has developed advanced simulators for high-performance, fighter-type aircraft. These devices simulate not only high-performance aircraft but also complex tasks such as air-to-air combat, aerial refueling, air-to-ground combat, and formation flying. With the increases in the sophistication of these simulators has come a corresponding increase in computational complexity. This complexity has negated the effects of higher computational speeds available in today's computers; thus, the transport delays have remained essentially constant. What has not remained constant, however, are the effects these transport delays have on the training effectiveness of these complex simulators. Because these modern simulators tend to be very complex in nature and consist of many computers interfaced with each other, the determination and measurements of the transport delays are often difficult. The effects these delays have on the simulation of a high-performance, fighter-type aircraft are also difficult to determine. The Air Force Human Resources Laboratory, Operations Training Division ~~(AFHRL/OT)~~ is currently completing the development of a new F-16C simulator with full-field-of-view visual display and no motion system. This paper describes the methods used to measure the transport delays that exist in this system and some of their effects on the training effectiveness of the simulation.

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MEASUREMENT AND EFFECTS OF TRANSPORT DELAYS IN A STATE-OF-THE-ART F-16C FLIGHT SIMULATOR

Scott J. Horowitz, Capt, USAF

OPERATIONS TRAINING DIVISION
Williams Air Force Base, Arizona 85240-6457

Reviewed and approved for publication by

Harold E. Geltmacher
Chief, Technology Development Branch

Paper presented at the 8th Interservice/Industry Training Systems Conference, Salt Lake City, Utah, 18 - 20 November 1986.

SUMMARY

The Air Force Human Resources Laboratory, Operations Training Division (AFHRL/OT) is currently completing the development of a new F-16C simulator with full field-of-view visual display and no motion system. This paper describes the methods used to measure the transport delays that exist in this system and some of their effects on the training effectiveness of the simulation. Because these modern simulators tend to be complex in nature and consist of many computers interfaced with each other, the determination and measurements of the transport delays are often difficult. The effects these delays have on the simulation of a high-performance, fighter-type aircraft are also difficult to determine. The objectives of this experiment were: (a) develop a method for easily measuring the transport delays of an existing simulator system; (b) measure the delays due only to the computer hardware; (c) measure the delays due to software and hardware combinations; and (d) determine the effects of transport delay, if any, on training in the simulator. To accomplish these objectives, a three-step process was outlined as follows: (1) design and construct hardware to interface with the cockpit and aero computations (basic side), and interface with the visual computer and display system (visual side) to provide a recording of inputs and responses; (2) analyze the delays expected, using a system block diagram and equipment performance specifications, and compare to the data collected in step 1; and (3) compare objective flight evaluations of the simulator using data collected during F-16C transition training conducted at AFHRL/OT. Results indicated the importance of making transport delay measurements on simulation equipment. These measurements verify that the device is actually performing according to specifications and, if not, show where the bottleneck is occurring. The method developed for measuring these transport delays is relatively simple and includes a unique and innovative technique for determining the output from a simulator visual display.

PREFACE

This paper documents a presentation given by Capt Scott J. Horowitz at the 8th Interservice/Industry Training Systems Conference held in Salt Lake City, Utah, on 18-20 November 1986. The research was conducted at the Operations Training Division of the Air Force Human Resources Laboratory, Williams Air Force Base, Arizona, under Work Unit 1123-03-84, *Analysis of Flight Simulator Transport Delay Effects*. This effort is in support of Technical Planning Objective 3, Training Technology, whose general objective is to identify and demonstrate cost-effective strategies and new training systems to develop and maintain combat effectiveness.

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MEASUREMENT AND EFFECTS OF TRANSPORT DELAYS IN
A STATE-OF-THE-ART F-16C FLIGHT SIMULATOR

I. INTRODUCTION

To perform research involving transport delay, it is first convenient to define a few terms related to transport delay. Figure 1 shows graphically the definitions of transport delay, equivalent time delay, and effective time delay. These delays are shown as a system's response to a step input and have the following physical significance: (a) Transport Delay - this is the type of delay that is associated with pure delay where the response is zero until the end of the delay period, sometimes referred to as "time to wiggle"; (b) Equivalent Time Delay - this delay is determined by assuming a functional form of the system response (usually a more simple model of the actual system) and determining the delay due to the term exp(1/t); and (c) Effective Time Delay - this delay is achieved graphically and is defined as the intercept on the time axis of the maximum slope of the system's response. For the simulator experiments conducted at the Air Force Human Resources Laboratory, Operations Training Division (AFHRL/OT), the type of delays investigated were pure transport delays.

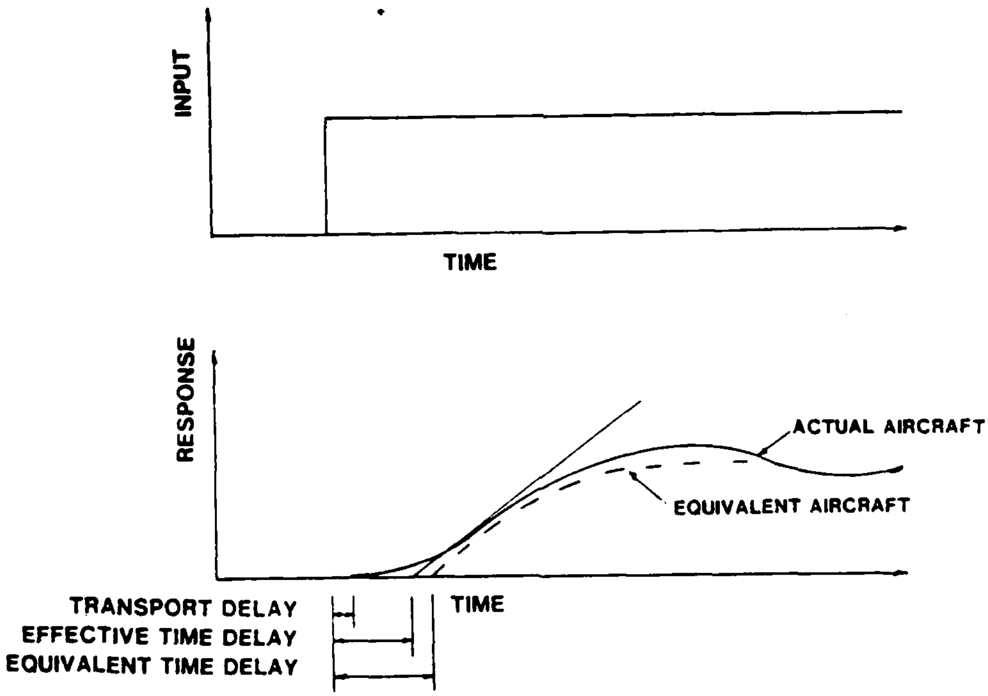


Figure 1. **Graphic Definition of Transport Delay, Effective Time Delay, and Equivalent Time Delay.**

The objectives of this experiment were: (a) develop a method for easily measuring the transport delays of an existing simulator system; (b) measure the delays due only to the computer hardware; (c) measure the delays due to software and hardware combinations; and (d) determine the effects on training in the simulator, if any, of transport delay (see Figure 2). To accomplish these objectives, a three-step process was outlined as follows: (1) design and construct hardware to interface with the cockpit and aero computations (basic side), and interface with the visual computer and display system (visual side) to provide a recording of inputs and responses; (2) analyze the delays expected, using a system block diagram and equipment performance specifications, and compare to the data collected in step 1; and (3) compare objective flight evaluations of the simulator using data collected during F-16C transition training conducted at AFHRL/OT.

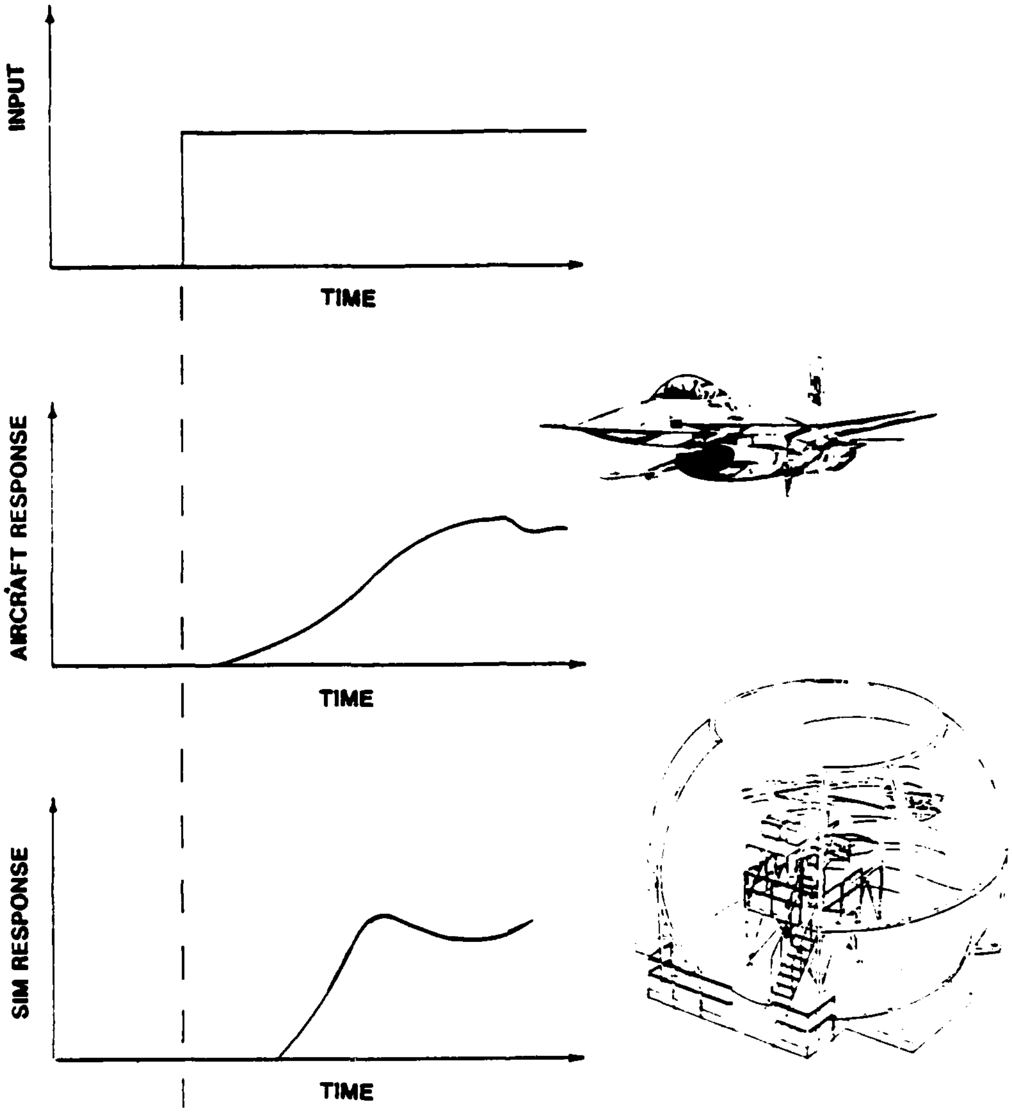


Figure 2. Simulator Fidelity.

II. EXPERIMENTAL SETUP

The interface designed and constructed for the basic side integration was relatively straightforward, due in part to the fact that the F-16C is a fly-by-wire aircraft and all information is available in analog or digital form. An interface card was designed and inserted in the system as seen in Figure 3. This card provided the pilot input as a stick voltage due to stick pressure as well as the signal the basic computer sent to the visual computer (pitch angle and roll angle). All this information was sent as analog signals to the strip chart recorder. The interface to the visual output was not as straightforward. Since there are delays associated with the calculation of the visual scene as well as delays due to the projection system (cathode-ray tube (CRT), light valves, etc.), it was decided that the best way to measure the visual output was directly from where the pilot would detect the visual scene; i.e., the display system itself. In order to accomplish this, a device was designed and constructed by Mr. Bill Lenenwiever of General Electric to convert the moving image on a CRT to an analog signal. This system is shown in Figure 4.

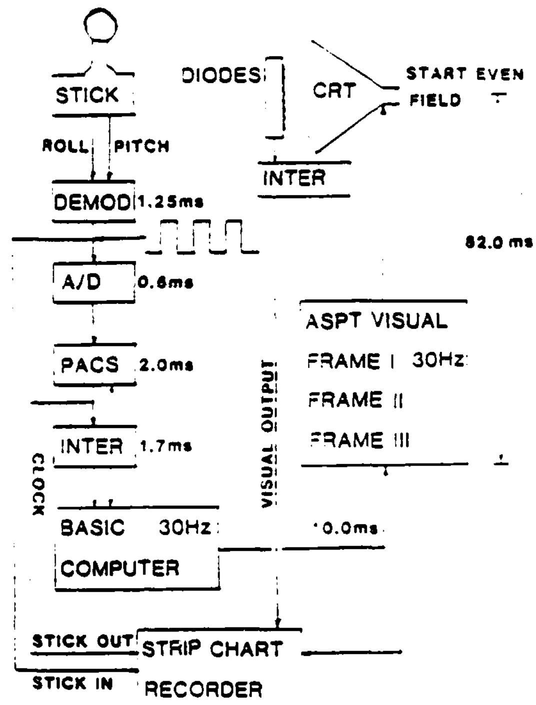


Figure 3. Experimental Setup.

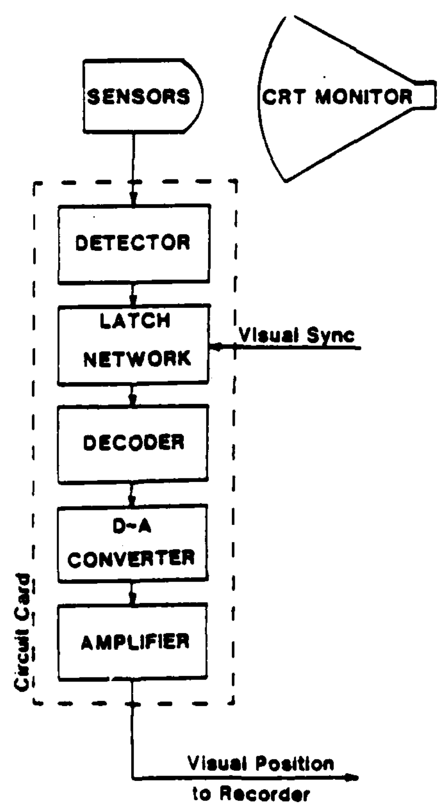


Figure 4. Visual-to-Analog (V-A) Converter.

The visual detector consists of five main components: (a) detector, (b) latch network, (c) decoder, (d) digital-to-analog (D/A) converter, and (e) amplifier. The detector consists of 16 photosensitive transistors mounted on a printed circuit (PC) board. Each sensor covers approximately 12 raster lines on the CRT monitor (6 odd field and 6 even field). The window definitions for the monitor were changed in the software such that several scan lines on the monitor corresponded to one scan line in the actual viewing field. The latching network is connected to the visual computer and is run by the 60Hz pulse that runs the system which synchronizes the latching network with the visual output. The latching network "holds" the information from the phototransistors for the whole field since the raster only momentarily illuminates the phototransistor and would result in a momentary spiked output rather than a continually increasing output as the horizon on the monitor moved. The information is then decoded, converted to an analog signal, and finally, amplified for use by the strip chart recorder. The delay in the electronics of the visual sensor account for approximately 12 nanoseconds and is not considered significant when compared to the quantities being measured.

The software used in the F-16C simulation had to be altered slightly to provide the outputs necessary for determining when the system had received the input from the control stick and sent the information to the visual computer. This presents a bit of a problem not unlike the Heisenburg uncertainty principle: You want to measure some quantity, but in the process of measuring it, you introduce changes and are now measuring a changed system. Much care needs to be exercised when making changes to the software of a flight simulator to ensure that the system is altered as little as possible. One of the major problems encountered in the software modifications for this program centered around the fact that the simulator did not have a "perfect" trim condition when taken off "freeze." This resulted in the aircraft's changing attitude without any stick input and thus, made it difficult to determine where the beginning of the measurement of delay began. Another problem encountered was that in order to have a signal to show when the basic computer finished its calculations required the software to send a signal to the D/A converter which sends a signal to the strip chart. The placement of this code in the simulation software is critical and should be as close to the actual transfer of data to the visual computer as possible. Modifications to the software were also introduced to study two types of delay: (a) delay due only to hardware and (b) delay due to hardware and software combined. To measure the delay due only to hardware, the code is changed to allow the stick input to be received by the basic computer while the entire aerodynamics package is skipped. At the system interrupt, the basic computer simply sends the visual computer either a 90-degree pitch up or down signal corresponding to whether the stick was pulled or pushed. This results in a step input at the stick providing a step output on the visual system. If the stick is driven by a square wave generator, then the output through the visual system will also be a square wave with a phase shift corresponding to the delay of the system. The setup that includes the software for the aerodynamics of the aircraft should yield the same transport delays as long as everything is working correctly. The only difference will be that a square wave input will not result in a square wave output, as the aerodynamics of the aircraft will act as a filter and distort the results, but the onset or "time to wiggle" should remain the same. If the test shows that the delays were increased, it is expected the increase will be in increments equal to the frame time of the system, as the software package may not have finished before the end of the frame. In this case the "frame drop" will be detected as a lack of output for one or more frame times (33.3ms for a 30Hz system). In testing the software, it is important to "exercise" the aero package by running the tests with the aircraft in different configurations.

Two methods of collecting data were used for these tests. To measure hardware delay only, the control stick input was replaced with a square wave generator. To select the frequency at which to drive the system, one must first determine the expected delay time and corresponding frequency of the system being measured. In this case, a maximum delay of about 150ms was expected; this is equivalent to 6.66Hz. Since each cycle of the square wave will input both an up and down pitch (right and left roll), the signal frequency must be no larger than half the

system frequency, or 3.33Hz. It should also be noted that if the frequency selected is exactly an integer fraction of the system frequency, the measured delay will be a constant because the input will always be in sync with the system. In order to measure the range of delays, the signal frequency should be slightly offset. The second method used to measure delay was a step input. This was accomplished with the aid of a pilot and a stick cutout switch. The pilot first trimmed the aircraft to fly straight and level. The next step was to turn on the cutout switch which removed the control inputs from the system. The pilot first trimmed the aircraft to fly straight and level. The next step was to turn on the cutout switch which removed the control inputs from the system. The pilot then input maximum stick deflection (actually pressure on the F-16C), and the cutout switch was deactivated. The result was that the system received a step input from a trimmed condition; this bypassed the problem of the simulator's inability to come off "freeze" in a trimmed state.

III. DISCUSSION OF RESULTS

The first analysis to be accomplished when measuring a simulator system for transport delay is to determine what delays are expected. In order to accomplish this, several items must be determined: (a) the delays of each of the system's components, (b) the type of visual perception model to be employed, and (c) how the components are interfaced. A schematic of the system used in this experiment is shown in Figure 3, which includes the transport delays for each of the system components. The different perception models basically refer to when to assume the pilot has perceived a change in the visual scene (i.e., the beginning of the first field, the end of the first field, or the end of the second field). In this experiment, the beginning of the even field (the second field) was used as the moment of perception. Using these definitions and the data in Figure 3, it is a relatively straightforward task to add up all of the delays in the system. Adding all of the delays in Figure 3 yields a total maximum transport delay of 134.84ms. Unfortunately, things are not quite so simple. In order to understand the internal workings of this simulator system, one must look at a timing diagram which shows how all of the devices are related to the system clock. Figure 5 shows the timing diagram for this simulator system. The most important item to note is that the location of the software commands for reading the control input is critical in determining the expected transport delay. As shown in Figure 5, this reading occurs 10ms after the beginning of the basic computer interrupt and thus, the expected delay should be 10ms less, or 124.84ms. Since the stick input may occur at any time, there is a range of delays that will be encountered. This range is determined by the length of the basic computer calculations, which for our system is 33.3ms. So, the total delay that should be expected will range from 124.84ms to 158.17ms, or an average delay of 141.51ms.

The raw data for this experiment were collected on an eight-channel strip chart recorder running at 200mm/sec. The channels used for this experiment were 1 through 7 and contained the following information: (1) 10Hz reference clock, (2) pitch input, (3) roll input, (4) basic computer pitch output, (5) basic computer roll output, (6) visual output, and (7) system clock (frame interrupt). An example of the raw data collected is shown in Figure 6.

A sample of the reduced data for these tests is presented in Figure 7. These figures show the transport delay as a function of sample number for the no flight equations case. Figure 7A shows the results for the entire system, Figure 7B shows the results for the basic computer side only, and Figure 7C shows the results for the visual side only. Figure 7A shows the measured delay varies by approximately 33.3ms, as expected, and shows the average total transport delay to be 148ms. This average delay is about 6.5ms over the expected result. Figure 7B shows the transport delay from the control input to the basic output is averaging 61ms, which is approximately 5.4ms greater than the 55.6ms delay expected. Figure 7C shows the visual system is

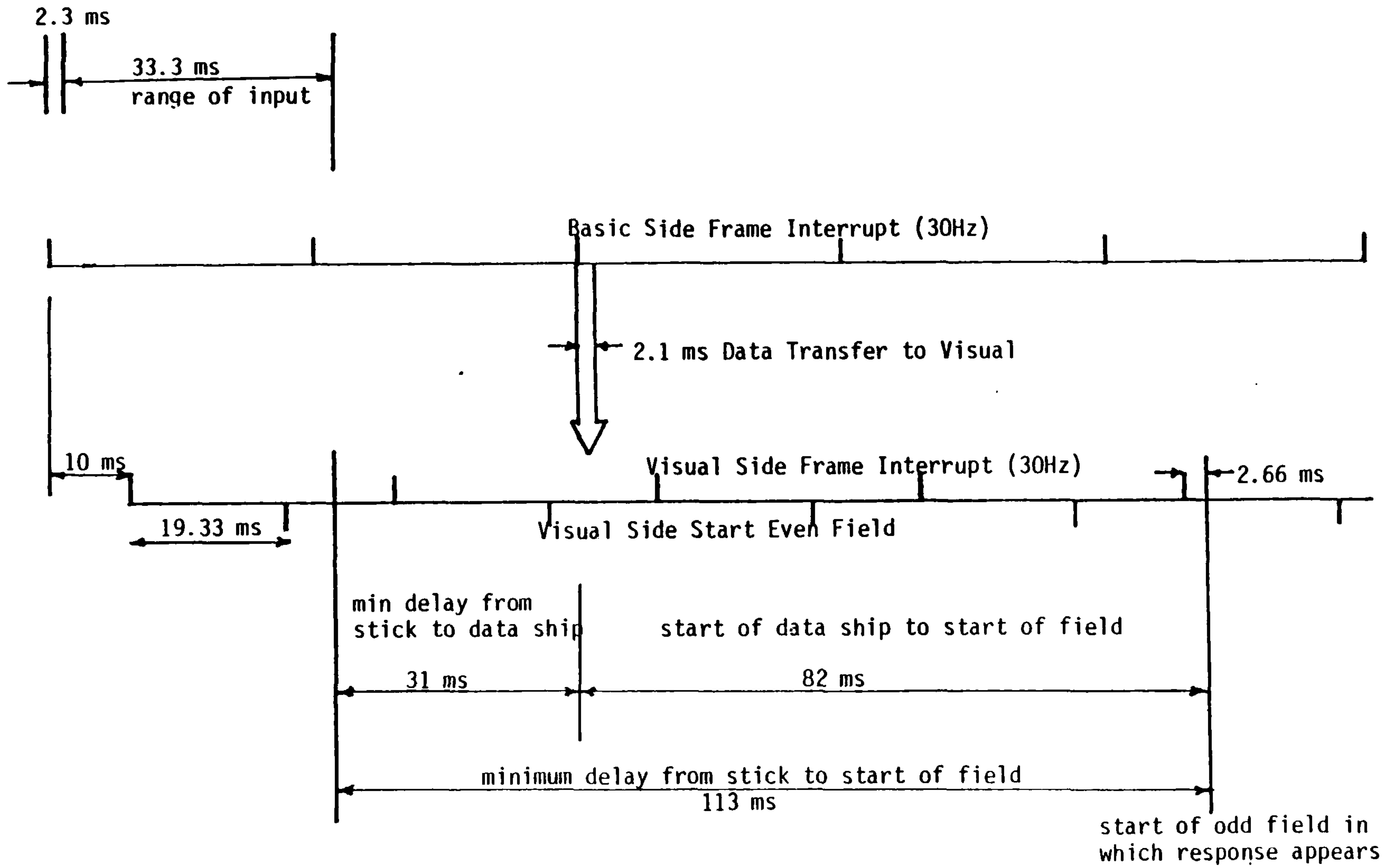


Figure 5. Frame Phasing and Transport Delay of F-16C Simulator.

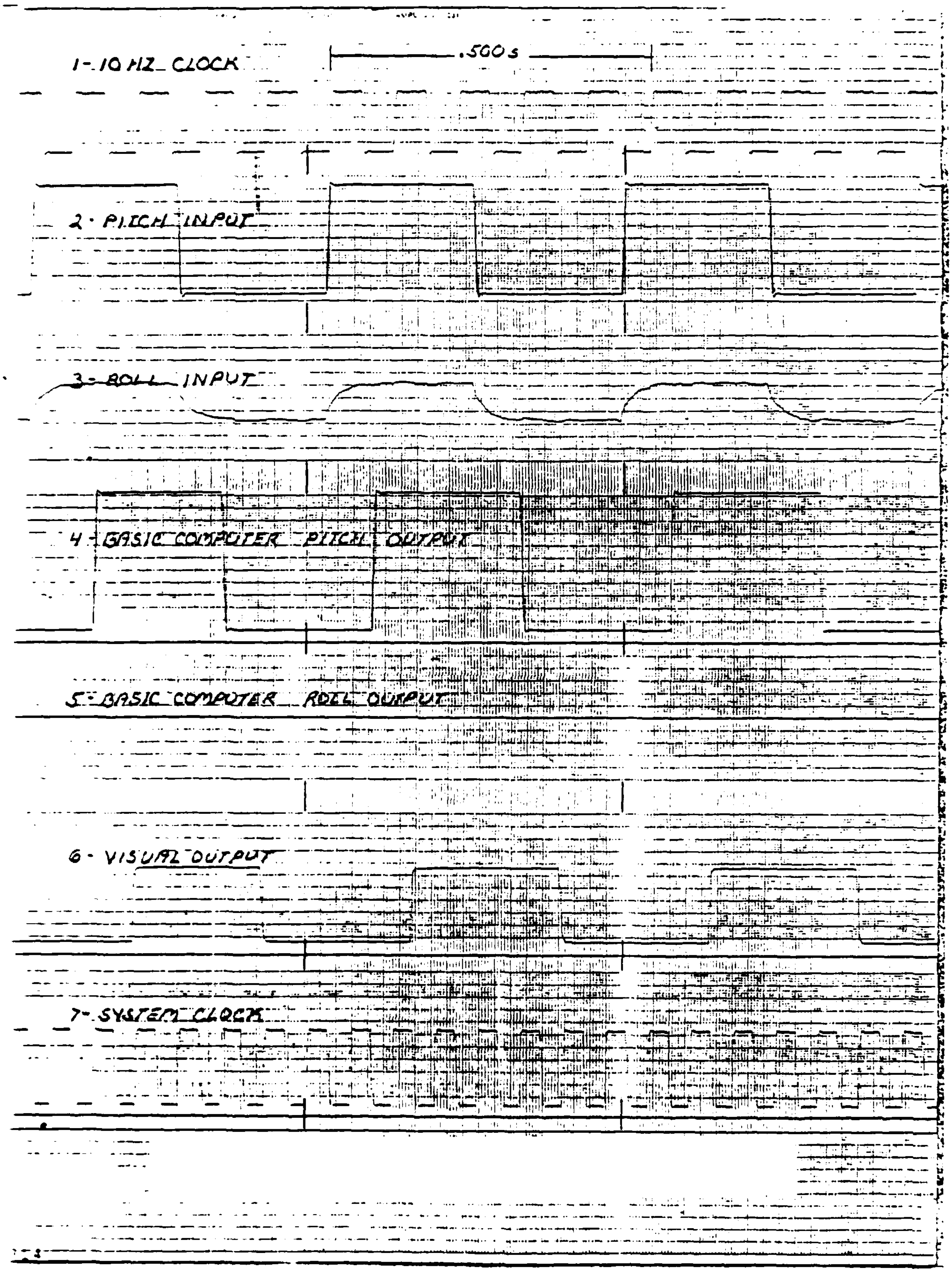
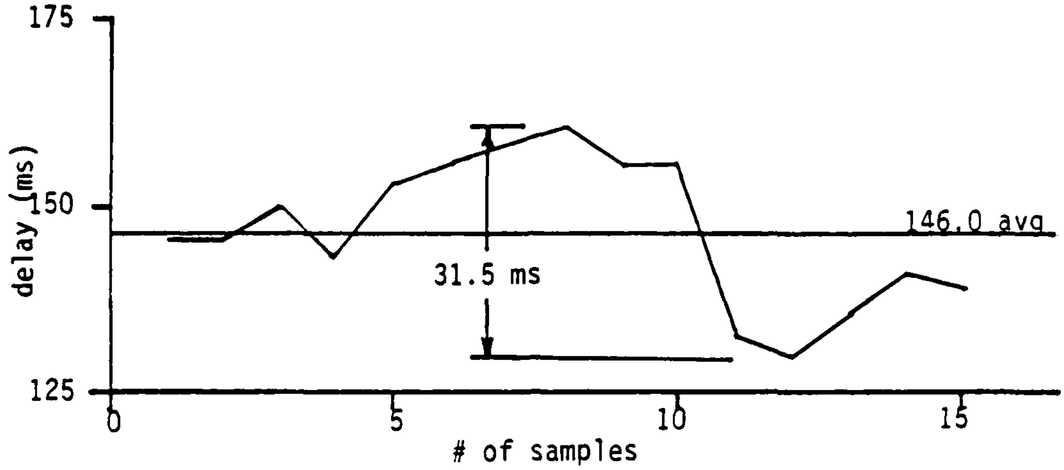
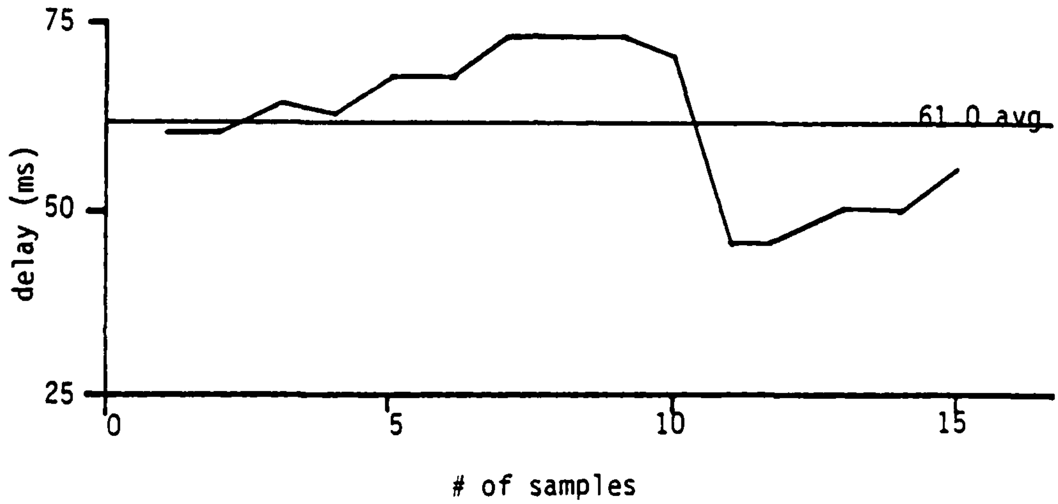


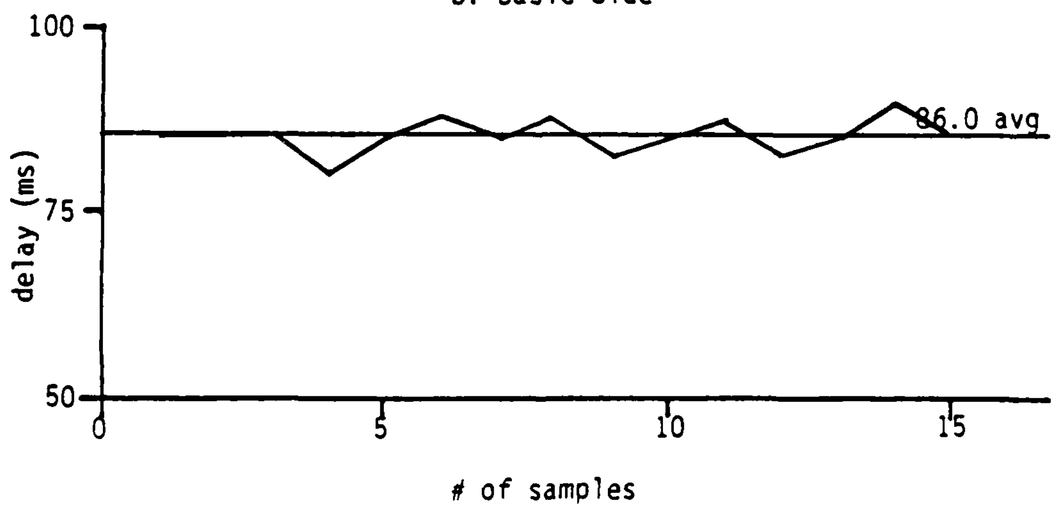
Figure 6. Strip Chart Output.



a. Total System



b. Basic Side



c. Visual Side

Figure 7. **Delays Without Flight Equations.**

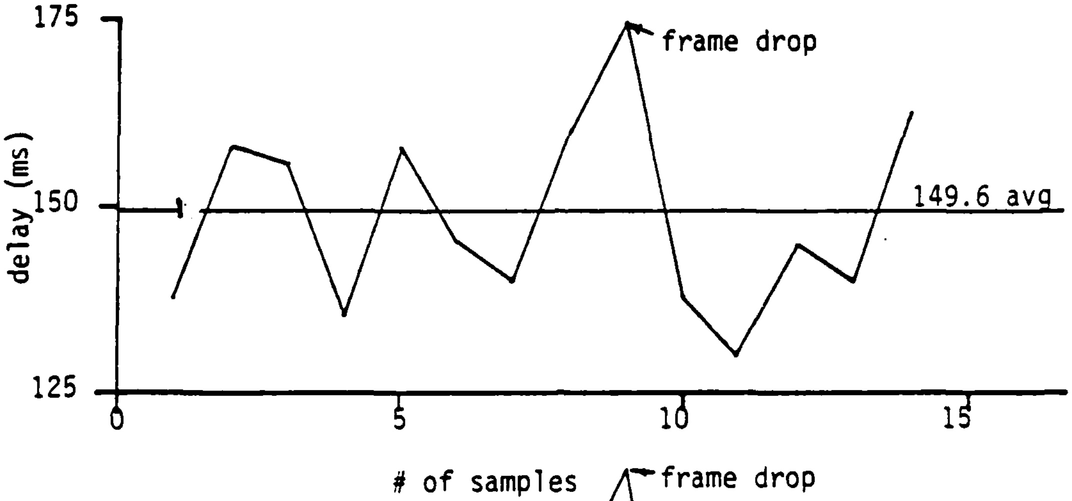
almost constant at 87ms, which compares favorably to the 86ms expected. It should also be pointed out here that the delays listed in Figure 3 for the devices between the control stick and the basic computer are considered worst-case delays. Therefore, the 5.4ms discrepancy is a minimum, and the actual difference may be as high as 10ms. This discrepancy was researched in some detail, and the only conclusion that could be drawn was that the interface between the programmable asynchronous communication system (PACS) and the basic computer is not operating as advertised. Figure 8 shows the same results, except that the software for the flight equations was included. For the flight condition tested, the software did not always finish in time for the data transfer to the visual system, as can be seen by the spikes in Figure 8B.

Figure 9 shows the average total transport delay as a function of the time since the beginning of the experiment. It is interesting to note that the results show the system operating well outside of specifications at the beginning of the experiment and asymptotically approaching the design specifications near the end of the experiment. What makes this result even more interesting is the fact that the contractors working on the simulator maintain that no changes to the system were made. It is left to the reader to draw any conclusions he/she wishes from this figure.

The final result that was obtained concerns the pilots' acceptance of the simulator. Before this experiment was begun, the simulator was being used for transition training and familiarization. The basic response from the pilots was that the simulator did not fly like the aircraft and did not handle well. By the end of the experiment the pilots who were interviewed still said that the simulator did not fly like the aircraft, but stated that the simulator was no harder to fly than the aircraft and that all tasks could be accomplished without much difficulty. Although this experiment hardly constitutes an in-depth examination of the handling qualities of a simulator as a function of the transport delay, it does indicate that a properly operating simulator with minimal transport delay will be more acceptable to the pilots.

IV. CONCLUSIONS

These results indicate the importance of making transport delay measurements on simulation equipment. These measurements verify that the device is actually performing according to specifications and if not, show where the actual bottleneck is occurring. The method developed for measuring these transport delays is relatively simple and includes a unique and innovative technique for determining the output from a simulator visual display. In order to determine the effects of transport delay on simulator handling qualities, another experiment is in progress that will utilize an in-flight simulator and ground-based simulators. This experiment will look at how of varying transport delay affects flight simulation user acceptance.



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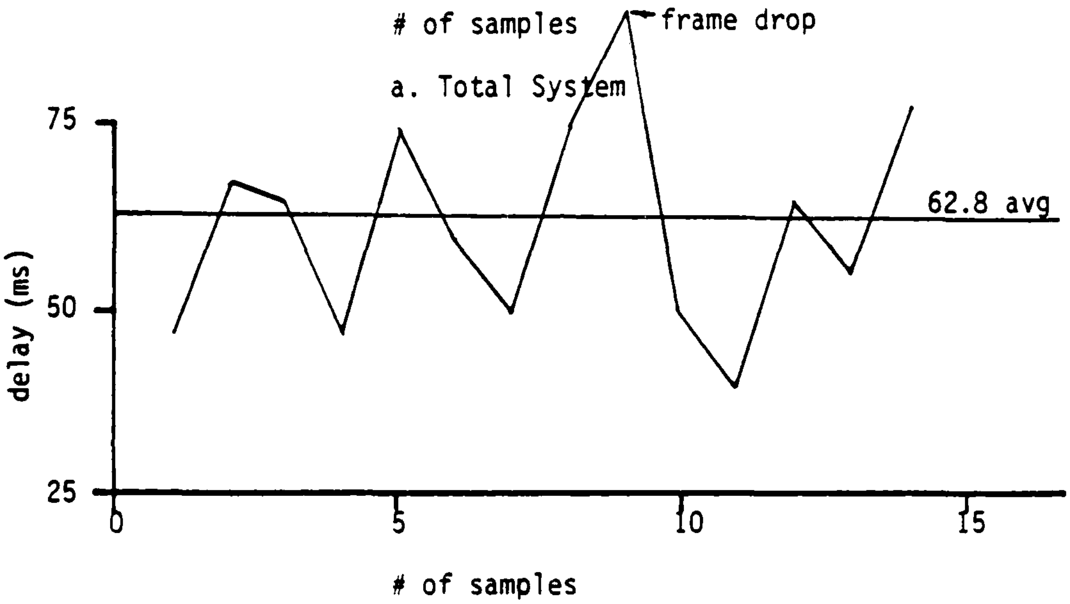
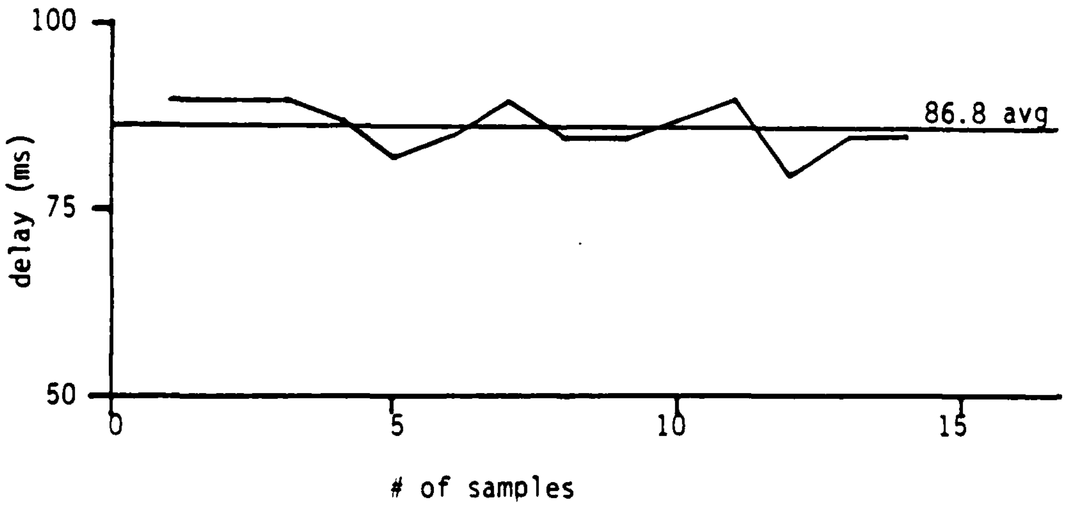


b. Basic Side



c. Visual Side

Figure 8. Delays With Flight Equations.

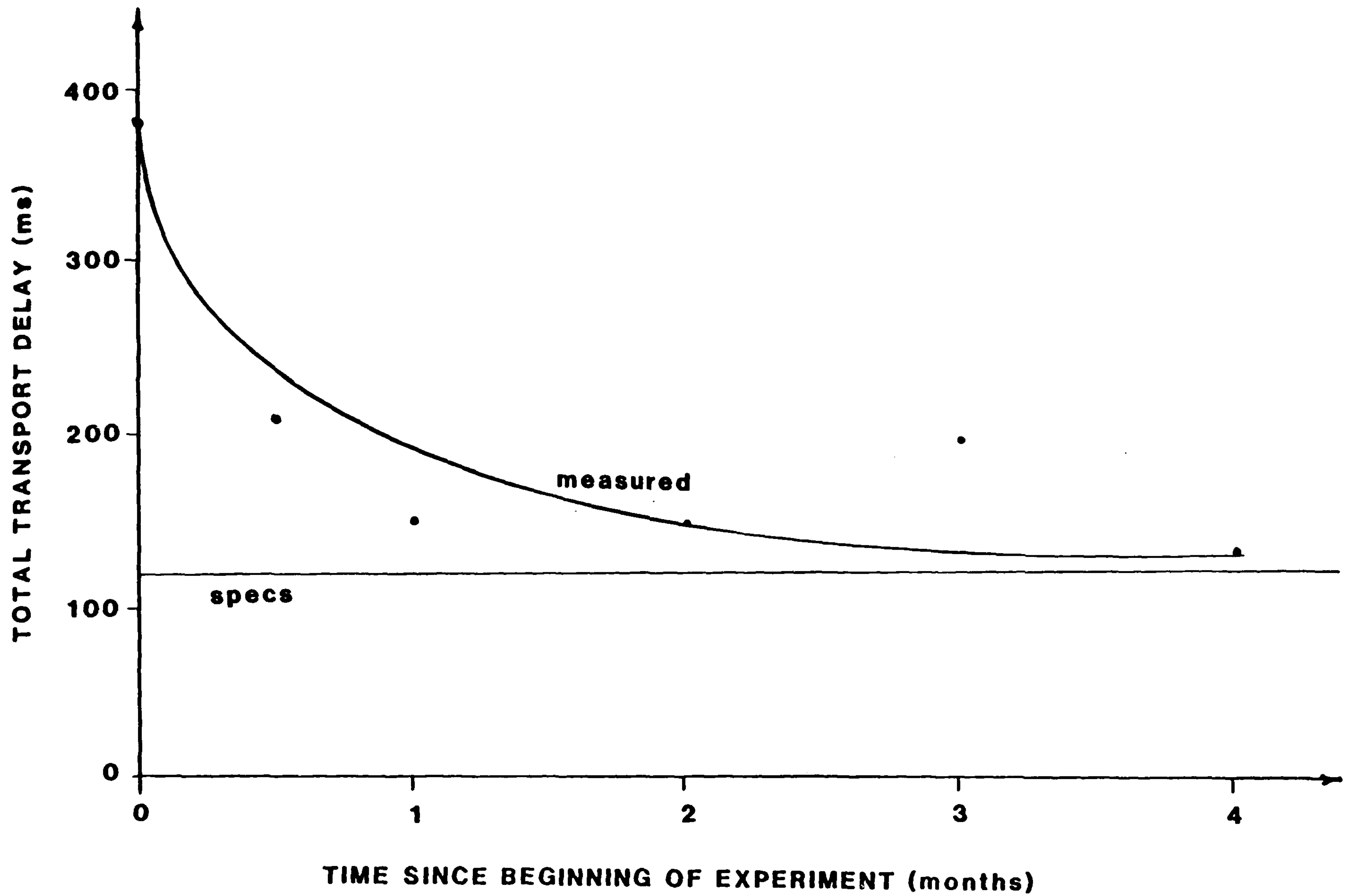


Figure 9. Average Transport Delay Versus Time.

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